Seismic characterization of carbonate platforms and reservoirs: an introduction and review

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Abstract: Improved seismic data quality in the last 10–15 years, innovative use of seismic attribute combinations, extraction of geomorphological data and new quantitative techniques have significantly enhanced understanding of ancient carbonate platforms and processes. 3D data have become a fundamental toolkit for mapping carbonate depositional and diagenetic facies, and associated flow units and barriers, giving a unique perspective on how their relationships changed through time in response to tectonic, oceanographic and climatic forcing. Sophisticated predictions of lithology and porosity are being made from seismic data in reservoirs with good borehole log and core calibration for detailed integration with structural, palaeoenvironmental and sequence stratigraphic interpretations. Geologists can now characterize entire carbonate platform systems and their large-scale evolution in time and space, including systems with few outcrop analogues such as the Lower Cretaceous Central Atlantic 'pre-salt' carbonates. The papers introduced in this review illustrate opportunities, workflows and potential pitfalls of modern carbonate seismic interpretation. They demonstrate advances in knowledge of carbonate systems achieved when geologists and geophysicists collaborate and innovate to maximize the value of seismic data from acquisition, through processing to interpretation. Future trends and developments, including machine learning and the significance of the energy transition, are briefly discussed.

Fundamental advances in seismic imaging of carbonate strata over the past decade have revolutionized scientific understanding of carbonate sediment accumulation and modification, with implications from hydrocarbon exploration to geomorphology and palaeoclimate change. These advances have been driven by oil and gas exploration and production, given the fact that carbonates are believed to host more than 60% of the world's oil reserves and 40% of the gas reserves (e.g. https://www.slb.com/technical-challenges/carbonates), but the data obtained are also increasingly being used to fundamentally reassess paradigms of carbonate platform development, architecture and post-depositional modification. Study of present-day or outcrop 'time-snapshots' do not reveal how carbonate platform development on millennial timescales and kilometric length scales was forced by long-term eustatic, oceanographic or tectonic factors, yet this forcing can now be determined from seismic images, their attributes interpreted using modern software, and correlated to information from boreholes or other geophysical surveys. Seismic attributes, singly and in combination, determined by the physics of acoustic-wave interaction with solid-rock matrix and its fluid-filled porosity are providing a novel toolbox with enormous potential to map heterogeneity within carbonate systems, and to improve understanding of depositional and diagenetic processes at scales rarely achievable from surface exposures.

Whilst 2D seismic provides key evidence of carbonate platform development and morphology in previously unexplored basins and stratigraphic intervals, improvements in acquisition, processing and filtering of 3D seismic data in basins with higher data density, as well as improved user-friendly interpretation software, have led to significant advances in carbonate geology. For example, seismic

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geomorphology, a concept first employed with spectacular results in passive-margin siliciclastic submarine fan settings with strong sand–shale impedance contrasts and simple overburden geology (Posamentier *et al.* 2007), is now applicable to carbonate platform systems in a variety of basin contexts (e.g. Ahlborn *et al.* 2014; Saqab and Bourget 2016; Wang *et al.* 2016; Paumard *et al.* 2017; Rankey 2017; Rinke-Hardkopf *et al.* 2018; Grant *et al.* 2019). Indeed, 3D seismic has become a fundamental toolkit for mapping carbonate depositional and diagenetic facies and associated flow units and barriers: for example, reticulate reef networks, lagoons, shoals or beach ridges, slope-collapse scars and toe of slope mass-flow deposits.

At a reservoir scale, the heterogeneity of carbonate pore systems, which result from complex depositional fabrics and their susceptibility to significant diagenetic modification, has long been recognized as a challenge for successfully appraising, developing and managing hydrocarbon fields. Accurate extrapolation of flow units between widely spaced wells has usually relied on conceptual models and analogues, or purely stochastic models that assume the geology is too complex to predict in a more deterministic manner. In a standout paper, Yose *et al.* (2006) demonstrated the potential for 3D seismic data to discriminate platform facies and flow units, and to populate them into a sequence stratigraphic framework for reservoir model building. Similar workflows have since become established practice. Inversion of seismic data, relationships of rock typing to rock physics and seismic resolution of depositional geometries now permit a more deterministic and iterative approach to reservoir modelling that is geologically conditioned and reduces uncertainty, allowing more accurate prediction of the inter-well volume (e.g. Rodrigues *et al.* 2016; Liu and Wang 2017; Ferreira and Lupinacci 2018; Lupinacci *et al.* 2020; Ghon *et al.* 2021). Further insights can be drawn in producing fields from integrating dynamic data with seismic characteristics and borehole log and core information (e.g. Warrlich *et al.* 2019). This approach can be augmented by cross-well seismic, especially where vertical imaging is complicated by overburden effects (Beavington-Penney *et al.* 2019). Major diagenetic porosity–permeability modifiers, such as fracture networks, palaeokarst cave systems and gas chimneys, can be identified and extracted from 3D seismic attributes, allowing well locations not only to target the best potential reservoir facies, but also to avoid critical drilling hazards (e.g. Zeng *et al.* 2011; Sun *et al.* 2013; Burberry *et al.* 2016; Tian *et al.* 2019; Aboaba and Liner 2020; Yan *et al.* 2020). In addition, the role of seismic interpretation in improving recovery from carbonate fields is increasingly important for security of energy supply during the critical transition period from exhausted easy-to-find large fossil fuel reserves towards a sustainable energy source future. As a logical extension, 4D seismic data will be essential to monitor CO_2 fronts in sequestration projects building on technology that has already been demonstrated for enhanced oil recovery (EOR) projects (e.g. Wang *et al.* 1998; Li 2003; Raef *et al.* 2005), as well as more recent research (e.g. Yenugu *et al.* 2015; Nuwara 2020).

This Special Publication illustrates some recent advances in the seismic characterization of carbonate platforms and reservoirs, and demonstrates substantial advances in data quality and visualization made since the last compilation of seismic imaging and interpretation in carbonate systems (Eberli *et al.* 2004). That previous collection of papers was published when 3D seismic data on carbonate platforms and reservoirs were becoming more widely available but before many of the major improvements in seismic acquisition (e.g. increased bandwidth and illumination), processing (noise, ghost and multiple removal, velocity modelling), resolution and visualization (attribute extraction and co-rendering, colour blends), and interpretation (autotracking, geobody extraction, stratal slicing and machine learning methods such as neural networks) that have featured in the past decade (e.g. Chandoola *et al.* 2020). Many more carbonate platforms of diverse ages have been imaged globally, including some shallow carbonate systems spectacularly imaged above deeper reservoir targets, such as the Neogene carbonates above the regional Cretaceous seal in the Browse and Carnarvon basins (discussed below). There have also been substantial advances in quantitative seismic interpretation, including inversion, fluid detection and rock-physics modelling (e.g. see Avseth *et al.* 2014). These constitute a technical discipline in their own right but still pose some of the greatest challenges in predicting reservoir properties from seismic data, especially where well data for model calibration are lacking. Because seismic interpretation is only the first stage in understanding carbonate reservoir potential in the subsurface, this contribution complements and should be considered alongside Geological Society, London, Special Publications, Volume 406 (Agar and Geiger 2015).

As the ability to extract additional quantitative information from seismic data has grown, seismic interpretation of carbonates has moved out of the arena of specialist geophysics to become an essential geological activity in exploration and field development. Geological knowledge of carbonate systems, how they are deposited and modified, and how they develop characteristic geometries with distinct rock properties (geobodies) is critically important for making robust and reliable seismic facies interpretations (e.g. Burchette 2012; Lanteaume *et al.* 2018) (e.g. Fig. 1). Whilst seismic geophysicists are actively collaborating with and learning from carbonate sedimentologists, so the latter are becoming more attuned to the importance of understanding key aspects of seismic data acquisition, processing and quantitative interpretation through rock-physics modelling. The cross-disciplinary approach means that new fundamental geological knowledge of carbonate depositional and post-depositional processes is generated even when the primary aim of seismic campaigns is the discovery and extraction of hydrocarbon resources (e.g. Purkis *et al.* 2015; Esestime *et al.* 2016; Sanford *et al.* 2016; Wu *et al.* 2016; Courgeon *et al.* 2017; Rankey 2017; Sayago *et al.* 2018; Smit *et al.* 2018; Tesch *et al.* 2018; Jackson *et al.* 2019).

For example, from analysis of 3D seismic data collected for hydrocarbon exploration, we now better understand how carbonate platform margin strata stack to form progradational, aggradational and retrogradational patterns that record a deep-time history of the accommodation and sediment production and transport variations (e.g. Dujoncquaoy *et al.* 2018; Tesch *et al.* 2018; Rankey *et al.* 2019), and how karst systems develop in 3D on carbonate platforms repeatedly exposed to subaerial weathering by relative sea-level falls (Carrillat *et al.* 2005; Hunt *et al.* 2010, Sayago *et al.* 2012). Both of these are illustrated in Figure 2. Subsurface 3D imaging has substantially impacted understanding of depositional and post-depositional processes in basin-floor and pelagic carbonates, showing them to be more dynamic on a large scale than many outcrop studies have been able to capture (e.g. Back *et al.* 2011; Smit *et al.* 2018) (Fig. 3). The possible roles of tectonics and fluid migration v. oceanographic and eustatic controls on the initiation of carbonate platforms are

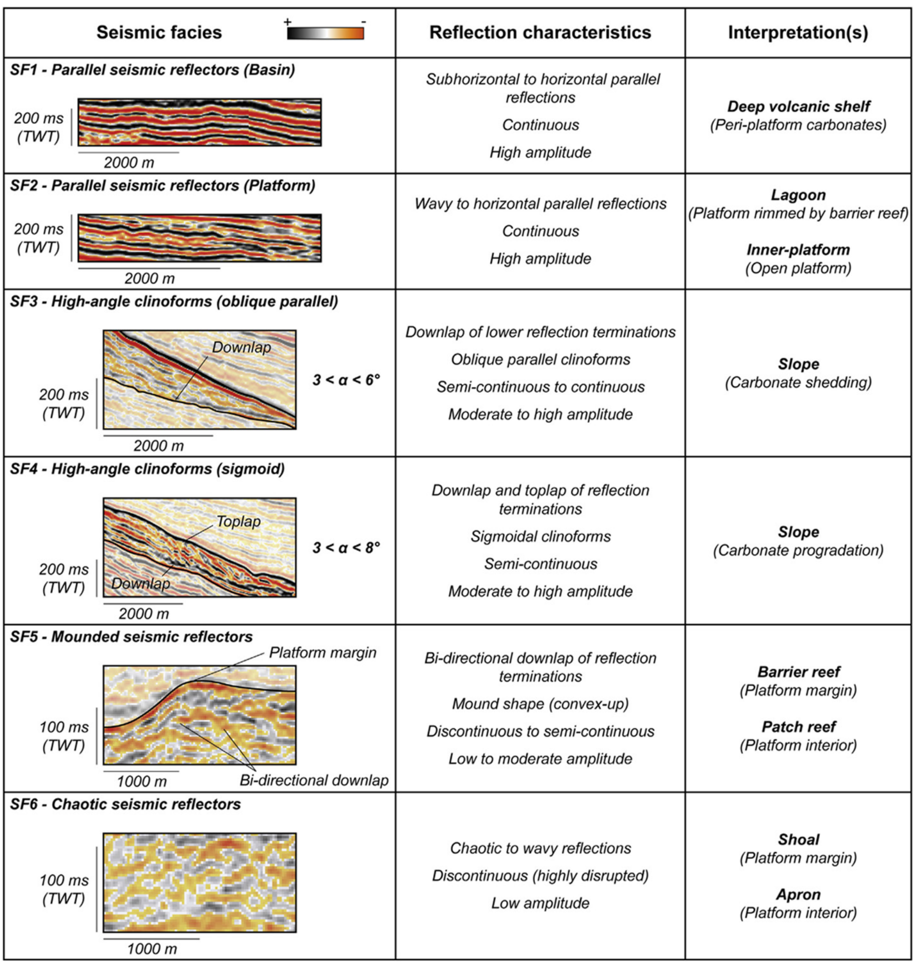

Fig. 1. (**a**) Example of carbonate seismic facies analysis.

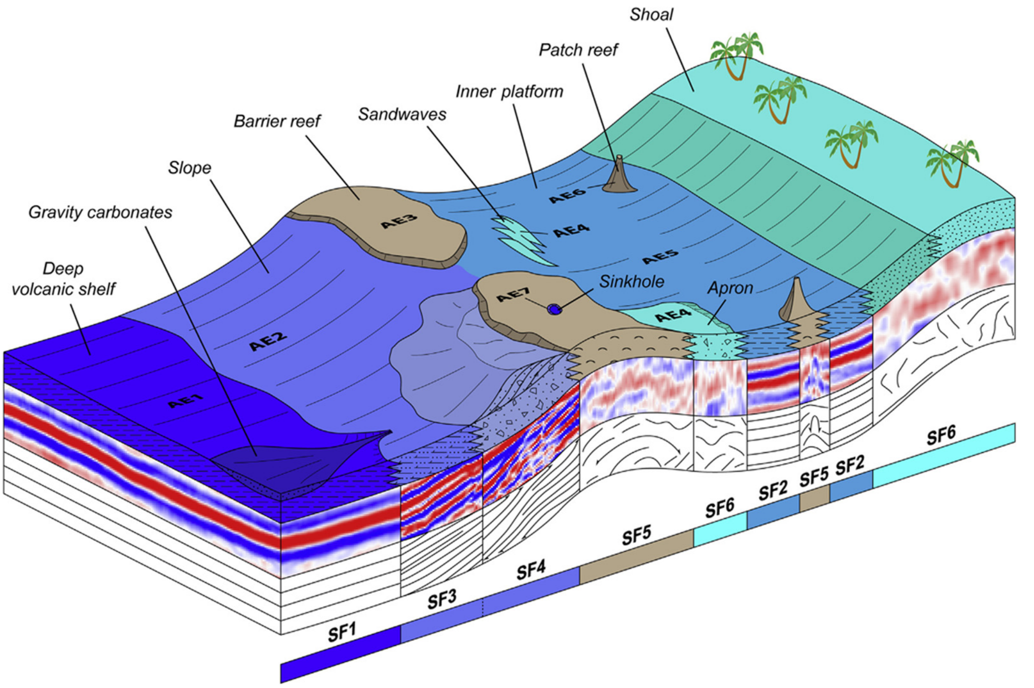

Fig. 1. *Continued.* (**b**) Interpretation with respect to carbonate depositional environments and their typical lithofacies associations. Because carbonate platforms vary in composition and depositional architecture through time and in response to tectonic, environmental and eustatic controls, geological knowledge is of paramount importance in the interpretation process. From Paumard *et al.* (2017, figs 3 and 13). TWT, two-way time.

also being reassessed with the aid of high-quality 3D seismic attributes and frequency blends (e.g. Saqab and Bourget 2018; Oppo and Hovland 2019). A further recent example that has dramatically increased interest in seismically imaged carbonates are the studies of the supergiant and giant non-marine carbonate reservoirs of the South Atlantic pre-salt play that are characterized by seismic and well data but have few direct analogues at outcrop (e.g. Buckley *et al.* 2015; Wright and Rodriguez 2018; Ferreira *et al.* 2019, 2021). As more seismic datasets are released into the public domain, usage to address fundamental questions of carbonate production, deposition and diagenetic modification, and how these processes record deep-time environmental change will undoubtedly increase (see the Discussion).

In addition to knowledge of deep-time carbonate systems acquired as a by-product of industry seismic campaigns, significant advances have been made using multichannel seismic data to study the Neogene–Quaternary history recorded in the flanks of modern carbonate platforms. This is commonly done in parallel with seabed imaging techniques such as multibeam bathymetry and sidescan sonar, plus borehole data. Attention has been focused on the Bahamas and the Maldives archipelago, and recently also in the South China Sea. This ability to integrate modern process sedimentology and quantitative physical oceanography with imaged depositional geometries and platform architectures extending into the recent geological past (when climate and eustatic conditions are better known) provides a unique 4D perspective for investigating carbonate platform dynamics that would otherwise be impossible or extremely difficult to capture (e.g. Betzler *et al.* 2016; Lüdmann *et al.* 2016; Principaud *et al.* 2017; Huang *et al.* 2020*a*). For example, these studies are providing a new understanding of the dynamic interaction of slope to slope-apron sedimentation with subsurface contour currents (Lüdmann *et al.* 2013; Tournadour *et al.* 2015; Wunsch *et al.* 2018). In turn, these studies have implications for exploration and field development in ancient settings, where currents have impacted the growth and flank facies distributions of isolated platform clusters (e.g. **Ting *et al.* 2021**).

The papers in this volume arose from an international gathering of more than 170 geoscientists from industry and academia at the Geological Society of London in October 2018 to discuss the seismic characterization of carbonate platforms and reservoirs. Fifty-six talks and posters addressed advances in

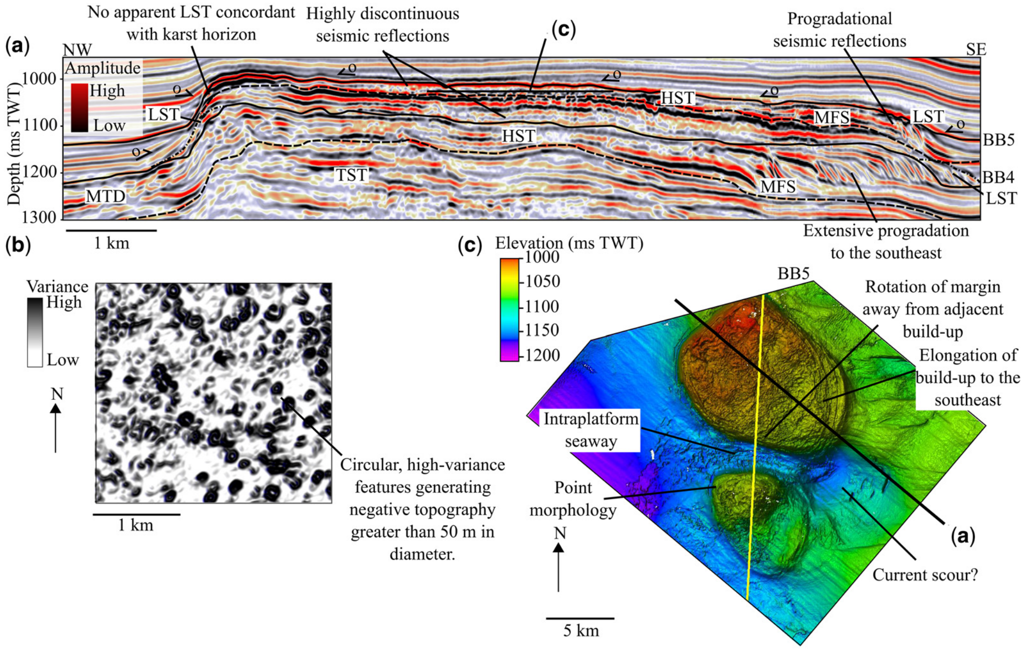

Fig. 2. Example of the sophisticated interpretations of carbonate platform architecture, depositional processes and history, sequence stratigraphy, and diagenesis that are possible with high-quality 3D seismic data. (**a**) Interpreted 2D seismic section of a Miocene isolated platform from the Browse Basin, offshore NW Australia. (**b**) Variance (coherency) attribute extraction showing karst sinkholes on a sequence boundary. (**c**) Two-way time structure map showing the platform geomorphology and its influence by ocean currents. Modified from Van Tuyl *et al.* (2019, fig. 6).

seismic imaging and modelling of carbonate strata, illustrating the variety of geological and reservoir characteristics than can be extracted from seismic data. The programme also explored the breadth of seismic technology applications in carbonates, from de-risking exploration plays and optimizing production strategies to understanding long-term and large-scale geological forcing of platform development. The volume likewise exemplifies both the substantial scientific and commercial value generated from careful integration of seismic geophysical and carbonate geological expertise. To be accessible to a broad geoscience readership the emphasis is on practical characterization and geological interpretation workflows rather than detailed theoretical treatments of rock physics and seismic inversion, although the latter are referenced where appropriate. The contributions are arranged into four themes, although there is necessarily some overlap:

- Leveraging seismic data in exploration and development of carbonate plays.
- The unique challenge of the South Atlantic pre-salt carbonate reservoirs.
- Novel developments in seismic modelling of carbonates.
- Seismic characterization of fluid flow and diagenesis in carbonates.

Leveraging seismic data in exploration and development of carbonate plays

Since the early days of frontier exploration driven primarily by 2D seismic surveys there has been a recognition that the unique combinations of depositional geometries (especially synoptic relief) and acoustic impedances (typically higher than surrounding shales ± sandstones) in carbonates can create distinctive responses. Coupled with a prevailing favourable view of prospectivity in shallow-marine carbonate platforms, driven no doubt by many exploration successes and giant fields in the Middle East, as noted by **Jiménez Berrocoso *et al.* (2021)**, there has been a historical predilection for interpreting carbonate build-ups where seismic geometries and amplitudes do not conform to well-known siliciclastic systems. Nonetheless, many carbonate prospects identified on seismic data have been drilled and found to consist of basement highs, volcanics or erosional remnants of siliciclastic systems (Greenlee and Lehmann 1993). Still others

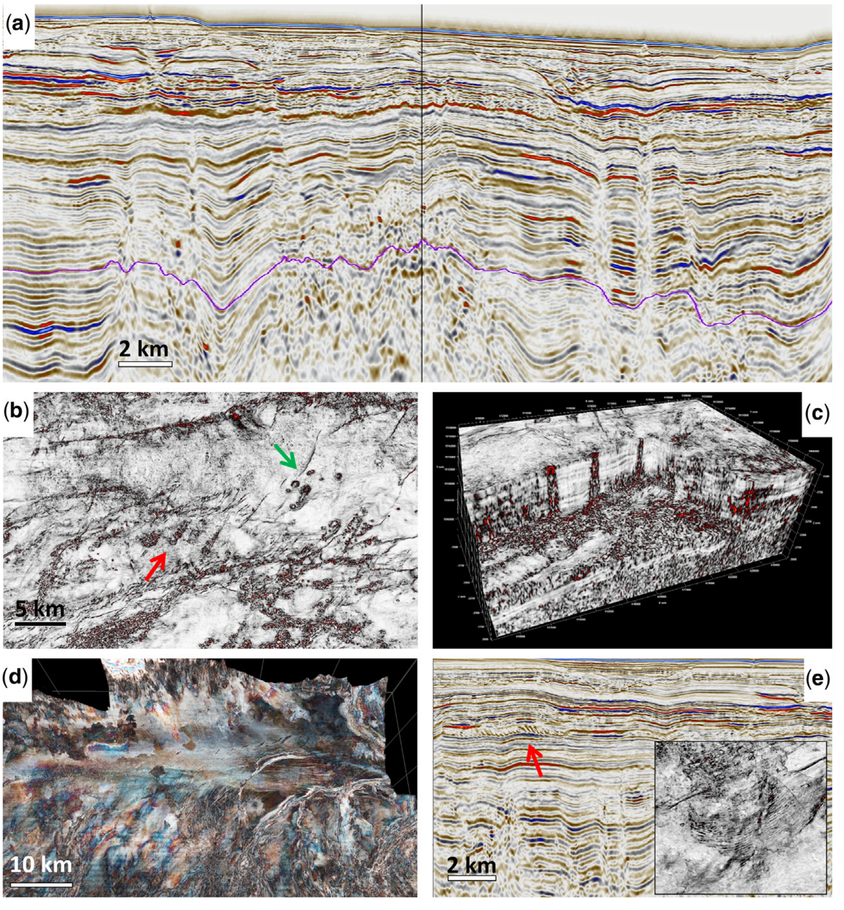

Fig. 3. Recent 3D seismic data from a Caribbean basin showing pipe-like structures with apparent collapse features and adjacent amplitude anomalies in Neogene post-rift basin-floor carbonates (above the purple horizon marker), plus submarine channels and slump features in the shallowest part of the section related to gravity-flow processes on an adjacent platform flank. (**a**) Arbitrary line through several pipes. (**b**) Depth slice through a variance attribute cube showing clusters of individual pipes (green arrow) and similar features aligned along fault trends (red arrow). (**c**) Box probe in a variance attribute cube showing pipe features. (**d**) Spectral decomposition extraction showing submarine channels and slope talus. (**e**) Arbitrary line showing a basin-floor slide block with internal deformation; inset is a variance slice through the same feature. Images courtesy of United Oil and Gas plc.

have been verified as carbonates but with insufficient reservoir quality or hydrocarbon column to be viable producing fields. Although such ‘false positive’ examples could provide valuable knowledge and data archives, very few of them get published as exploration companies are quick to move onto new opportunities and teams are redeployed. The situation is better where discoveries are made, and associated appraisal and development drilling ensues, with the benefit that the seismic interpretations of the carbonates are validated and refined with additional sedimentological, biostratigraphic, petrophysical and rock-physics analyses. An increasing number of seismically based carbonate exploration successes are being published, with some regional biases that reflect the commercial sensitivities associated with the plays and the confidentiality thresholds of the operators. In some cases, the seismic data have been shared with academic researchers, allowing more in-depth interpretation and analysis of depositional, structural and diagenetic topics that advance knowledge of carbonate systems but may not be business priorities for exploration and development teams.

The huge increase in both the use and quality of 3D seismic data, and in the visualization and interpretation software, over the past decade has made it easier to recognize and characterize some carbonate platforms. This is due to the obvious benefit of

3D imaging, increased resolution and reduction in migration artefacts caused by out-of-plane reflections, and through the variety of seismic surface and volume attributes that are available to tease out geomorphological details and map facies, and structural and diagenetic trends (e.g. Yose *et al.* 2006; Rafaelsen *et al.* 2008, Yin *et al.* 2010; Janson *et al.* 2011; Wang *et al.* 2016; Di Lucia *et al.* 2017; Paumard *et al.* 2017; Makhankova *et al.* 2020; **Embry *et al.* 2021**). However, in frontier and emerging plays it is still the norm that a potential carbonate target is first identified on 2D data, risked and economically evaluated, prior to making a decision for investment in 3D data. Moreover, the greater cost and complexity of shooting 3D surveys onshore, especially in relation to well cost differentials, means that relatively few onshore carbonate prospects benefit from 3D seismic. Selection of survey type and acquisition parameters for the 3D surveys are fundamental to successfully imaging and characterizing of the platform, and the authors' experience is that companies increasingly appreciate the importance of geological specialist involvement at the planning stage. The same applies for other play types that have to be imaged beneath carbonate overburden, because the relatively high but heterogeneous impedance and high-velocity properties of carbonates can have a major impact on acoustic energy transmission and its spatial variability. This is exemplified by **Embry *et al.* (2021)**, where a carbonate target was only identified following pre-stack depth migration due to complex velocity contrasts in the overburden.

Addressing the challenges in confidently recognizing carbonate platforms from seismic data, Burgess *et al.* (2013) published a set of objective criteria for identification of isolated carbonate buildups. These were accompanied with a simple scoring scheme based on the application of these criteria to 234 published examples, to de-risk interpretations and determine which features have the greatest discriminatory power when alternatives such as volcanics, tectonic features and basement highs are considered. Whilst the authors candidly acknowledged the limitations and remaining challenges in the approach, and notwithstanding its focus on a particular type of isolated high-relief carbonate platform, it provides a systematic and geologically grounded approach that has been adopted, expanded and refined for internal use by several major exploration companies such as Repsol and Equinor. This relies on expansion of the image database through incorporation of more examples, tackling other carbonate platform types that are less morphologically striking, and considering combinations of criteria or more granularity in the weightings (Burgess *et al.* 2013). Whilst internal databases are likely to contain commercially sensitive examples and be viewed as providing competitive advantage, there is hope that a greater sharing of data and workflows will become possible, perhaps following the model of the Virtual Seismic Atlas (https://seismicatlas.org/). Additionally, large-scale seismic datasets are beginning to be available to academic users by some regulatory authorities, a key example being 2D and 3D datasets on the NW continental shelf of Australia (Browse and Carnarvon basins) held by Geoscience Australia. This has led to several significant papers and theses documenting the stratigraphic and geomorphological development of Neogene carbonate platforms, and their tectonic and eustatic context (e.g. Rosleff-Soerensen *et al.* 2016; Saqab and Bourget 2016; Belde *et al.* 2017; Rankey 2017; Tesch *et al.* 2018; Van Tuyl *et al.* 2019). There are also exiting new possibilities for employing multi-attribute machine-learning processes for seismic recognition and facies characterization of carbonate prospects (Roden and Sacrey 2017; Chopra *et al.* 2018; Pattnaik *et al.* 2020; Wu *et al.* 2020), although again this is most likely to be trialled in large companies with access to multiple datasets. It should be added that this kind of application has been available for many years (e.g. Baaske *et al.* 2007). However, the rapid increase in computing power plus the range of new seismic attributes from modern surveys will be likely to produce a paradigm shift in how carbonates are routinely interpreted from 3D seismic data.

Of the many published seismic images and studies of carbonate platforms in the past *c.* 10–15 years, many have been focused on the Neogene of SE Asia, and include some excellent detailed analyses of seismic geomorphology (e.g. Posamentier *et al.* 2010; Kŏsa *et al.* 2015; Paumard *et al.* 2017), internal and external seismic geometries, faulting and facies (e.g. Zampetti 2010; Fyhn *et al.* 2013; Widarmayana *et al.* 2014; Jamaludin *et al.* 2018; Rankey *et al.* 2019; Makhankova *et al.* 2020), and detail of relationships between contemporaneous carbonate and siliciclastic depositional systems (e.g. Tcherepanov *et al.* 2008, 2010; Saller *et al.* 2010; Kŏsa 2015). The reason for this geographical skewing of published studies partly reflects a prevalence of high-relief isolated reefal carbonate platforms, commonly developed in late synrift to post-rift tectonic regimes and buried beneath acoustically soft distal siliciclastics when the platforms drowned owing to various environmental or relative sea-level changes. The characteristic shapes and high impedance of these platforms makes them relatively easier to identify (see above) than platforms with less steeply inclined flanks, so proportionately more of them have been drilled and more discoveries made. Reservoir quality within them is often good but typically distributed in complex ways, in response to variably interdependent depositional and diagenetic processes, so data-rich appraisal wells are commonly required and used for further calibration of the seismic. In this volume, **Ting *et al.* (2021)** illustrate the value of a high-quality regional 3D mega-survey in the Central Luconia province (South China Sea) for understanding environmental and tectonic controls on the flank geometries and reservoir facies development of multiple isolated platforms previously studied in isolation or on a loose grid of 2D lines and with a few small discrete 3D surveys. Using seismic geometries and attribute combinations, the impacts of monsoonal wind-driven submarine currents, nearshore tidal currents, antecedent topography and syndepositional tectonics are shown to have varied in relative importance across the province in a consistent and predictable manner. However, clusters of large platforms are also shown to have modified the current circulation and resulted in atypical facies distributions on adjacent or intervening smaller platforms.

Late Paleozoic platforms of the Norwegian Barents Sea represent another carbonate mega-play with much published seismic data and interpretation, facilitated by a culture of information sharing, centralized oversight of well and seismic data at the Norwegian Petroleum Directorate, and national policies setting out time limits on data confidentiality. Published studies have provided a unique window on 3D carbonate geomorphology, including the first evidence of large-scale reticulate build-ups that are impossible to appreciate from size-limited 2D outcrops (Elvebakk *et al.* 2002; Rafaelsen *et al.* 2008; Colpaert *et al.* 2010; Purkis *et al.* 2015). Seismic data have also been generating important knowledge on the 2D (surface) morphology and 3D distribution of palaeokarst networks (Carrillat *et al.* 2005; Hunt *et al.* 2010, Sayago *et al.* 2012), as well as on the spatial and temporal evolution of carbonate–evaporite relationships (Ahlborn *et al.* 2014). Other notable carbonate plays with recently published seismic images and interpretations are the Permian platforms flanking the Zechstein salt basin (Patruno *et al.* 2018; Grant *et al.* 2019), the Cretaceous–Neogene post-salt platforms offshore Brazil (Bueno *et al.* 2014; Buarque *et al.* 2017; Cruz *et al.* 2019), Paleogene–Neogene isolated platforms in the Indian Ocean (Shazad *et al.* 2018, 2019) and Early Paleozoic carbonate platforms from onshore China basins (e.g. Huang *et al.* 2020*b*).

Relatively less seismic data has been published since the mid–late 2000s from some of the 'classic' petroliferous carbonate systems, such as the Jurassic–Cretaceous of the Middle East, the Gulf of Mexico, the Paleozoic intracratonic basins of North America and the Western Canada Sedimentary Basin. These are 'mature' provinces and/or onshore basins where drilling is relatively cheap and targeted seismic campaigns directed more towards commercially sensitive development projects, improved reservoir characterization and geomodelling than towards identifying new plays, leads or prospects. Geopolitical factors also likely play a role in the extent to which data and interpretations reach the international/western scientific media, and it is more common to find integrated reservoir characterization studies involving seismic attributes and inversion workflows reported in technical conference proceedings than in 'mainstream' geoscience journals. On the African Atlantic margin, carbonate exploration is still at an early stage with few commercial discoveries other than in the Albian (post-salt) carbonate and mixed carbonate–siliciclastic shelf systems of Angola and Gabon; and although an extensive Jurassic–Neocomian carbonate shelf is present from Morocco to Guinea, it is little tested and consequently few seismic images currently exist in the public domain. The same is true of the conjugate margin, except for the Jurassic Abenaki platform on the Scotian Shelf, which is relatively well documented (Kidston *et al.* 2005; Harvey and Macdonald 2013). There are also a growing number of integrated carbonate seismic and well studies from Chinese onshore basins, although typically with a development rather than exploration focus, and employing seismic attributes for lithological and diagenetic studies, especially of karstification (see the 'Seismic characterization of fluid flow and diagenesis in carbonates' section later in this chapter).

The Caribbean is a region of active frontier and emerging basins where relatively few ancient carbonate platforms have published 3D seismic data (e.g. Bunge *et al.* 2017), and it was also a region characterized by localized but frequent tectonic and volcanic activity that can provide alternatives to carbonate platform interpretations. **Jiménez Berrocoso *et al.* (2021)** discuss an undrilled putative Miocene carbonate platform from the Lesser Antilles, using a modern 3D seismic survey carefully integrated with regional geology, structural restoration and potential field data, and applying the Burgess *et al.* (2013) scorecard. They persuasively show that the seismic geometries, facies and ancillary data combine to support a carbonate platform interpretation, possibly analogous to the Perla Field in the Gulf of Venezuela (Castillo *et al.* 2017), but that the data fail to negate alternatives such as an eroded siliciclastic deposit. The study demonstrates the importance of mitigating exploration risk by integrating seismic interpretation with all the geological and exploration data available. It also makes the important point that frontier carbonate prospects may carry a significant reservoir risk that can only be addressed by drilling, provided other risk elements of the petroleum system are favourable.

Whilst modern 2D and 3D seismic data are unlocking new knowledge about carbonate platform development and architecture, over stratigraphic intervals and length scales that are not otherwise accessible, challenges remain in characterizing the rock–fluid properties and reservoir potential of these carbonates at an exploration stage where there are few or no data-rich wells that penetrate the platforms themselves. Although carbonates are mineralogically simple, their elastic properties are very difficult to predict because of the variety in size, shape and connectivity of pore systems, the large impedance contrast between this heterogeneous fluid-filled porosity and the surrounding matrix, and the lack of simple V_P–V_S relationships (discussed further below). This means that generic rock-physics attributes are lacking, other than for texturally simple and homogeneous carbonates, and it can even impact identification of carbonates where other geometric attributes and contextual data are equivocal. For example, a stratabound high-porosity unit in a carbonate platform could have the same impedance as a transgressive shale, so careful geologically guided seismic interpretation is always fundamental.

Because of the aforementioned challenges, reservoir-quality assessments involving quantitative interrogation or inversion of the seismic data from undrilled carbonate prospects typically has to be model driven, and conditioned by data from wells in analogue fields that are considered to be geologically comparable. **Embry *et al.* (2021)** combined seismic geometries, seismic stratigraphy and multi-attribute analysis to record the depositional history, geomorphology and facies architecture of a Cretaceous carbonate platform margin prospect in the Gulf of Mexico. The use of frequency decomposition and colour blending techniques on the high-quality 3D survey generated spectacular images of facies belts, reef morphologies and palaeokarst sinkholes. The study discusses an iterative workflow employed to interpret seismic facies in terms of rock properties using analogue long-offset well data and seismic forward modelling, leading to optimal placement of an exploration well and subsequent post-drill validation of the conceptual model.

The unique challenge of the South Atlantic pre-salt carbonate reservoirs

Following the 2006 Tupi discovery (now known as the Lula Field) in the Lower Cretaceous lacustrine carbonates of the Santos Basin, Brazil, the pre-salt carbonate systems have become the focus of intensive interest both from the petroleum industries and academia. Little was published on the prolific petroleum system of these lacustrine carbonates in the South American and conjugate African margin rift basins for over 10 years, hampering regional comparisons and development of holistic interpretations. They are now known to be associated with significant depositional, diagenetic and structural heterogeneities, with corresponding challenges for reservoir-quality prediction, dynamic modelling and reserve determinations. To unlock the exploration potential, assess the value of existing assets and define the field development strategy of these lacustrine carbonate reservoirs requires a multidisciplinary approach that integrates detailed understanding of the tectonic setting, stratigraphic evolution and impact of diagenesis. A fundamental objective is to determine how lacustrine carbonate heterogeneity is reflected by changes in seismic geometries and seismic facies.

Since 2018, in parallel with rapid field-development strategies and with most attractive acreage positions being taken, there has been a significant increase in pre-salt carbonate publications, primarily with examples of seismic expressions of the lacustrine carbonate systems in the field (e.g. Barnett *et al.* 2018; Correa *et al.* 2019; Ferreira *et al.* 2019; Menezes de Jesus *et al.* 2019; Penna *et al.* 2019; Olivito and Souza 2020; Ferreira *et al.* 2021). In this volume, two key articles from Barnett *et al.* (2020) and Minzoni *et al.* (2021) make an important contribution to the study of pre-salt lacustrine reservoirs from both a field-development and regional/exploration context, respectively. To place these in context, it is important to appreciate both the range of pre-salt reservoir types and the ongoing debate associated with their occurrence and origin.

As summarized by Saller *et al.* (2016), Sabato Ceraldi and Green (2017) and Wright (2021), the South Atlantic pre-salt lacustrine carbonates comprise three very different primary reservoir types (Fig. 4a). These are associated with major temporal changes in lake-water chemistries and structural positions on the basin margins (Fig. 4b). The oldest lacustrine carbonate reservoirs are biogenic (BIO), dominated by accumulations or ‘coquinas’ of bivalve molluscs (Fig. 4a), and are interpreted as having been deposited in relatively freshwater to saline waters (i.e. Thompson *et al.* 2015; Muniz and Bosence 2018; Pietzsch *et al.* 2018; de Oliveira *et al.* 2019; Olivito and Souza 2020). In the Santos Basin, these belong to the Itapema Formation. The low-diversity fauna and the general absence of ‘normal’ lacustrine carbonate producers (such as charophytes) points toward environmentally stressed conditions (e.g. Muniz and Bosence 2018; Olivito and Souza 2020). Evidence from studies of faunal diversity is also supported by geochemical data (Pietzsch *et al.* 2018). Although there are excellent analogues for these deposits at outcrop (e.g. Carvalho *et al.* 2000; Favoreto *et al.* 2021), uncertainties have persisted over the geometries of large-scale deposits and the hydrodynamic–depositional processes responsible for such large bioclastic accumulations.

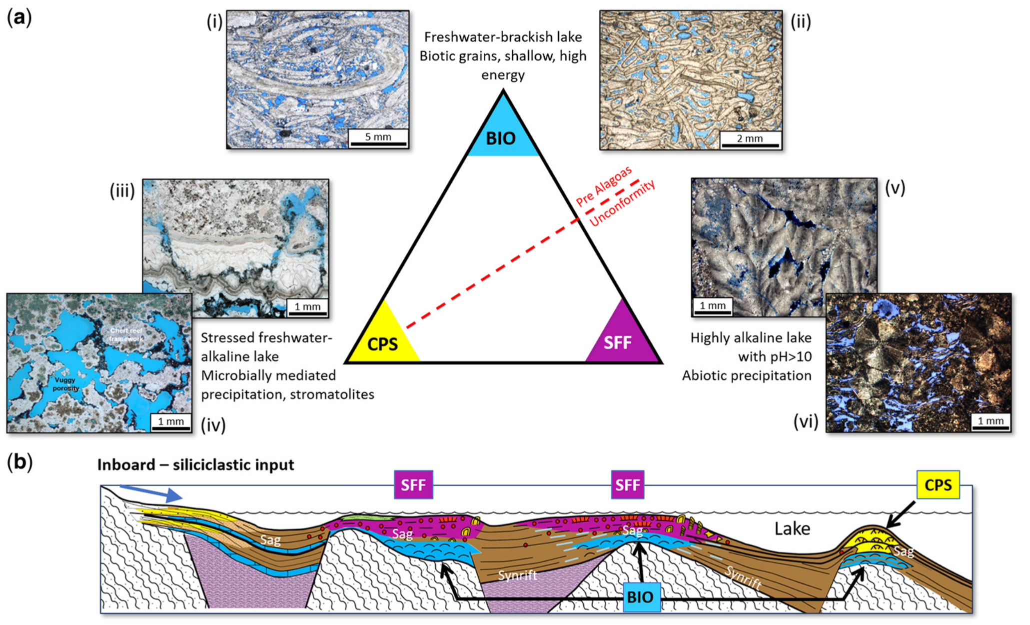

Fig. 4. (**a**) Proposed three-fold division of pre-salt reservoir types in the South Atlantic comprising bioclastic (BIO), clotted peloidal silica (CPS) and spherulite fibrous fan (SFF) ('shrubs') type facies associations, as named after the principal components; modified after Wright and Barnett (2017); Wright 2021 pers. comm. Photomicrographs (i) and (ii) are reproduced from Olivito and Souza (2020), (iii) is from Cazier *et al.* (2014), (iv) from Vieira de Luca *et al.* (2017) (© AAPG 2017, reprinted by permission of the AAPG whose permission is required for further use), and (v) and (vi) is from Wright (2021). (**b**) Diagram showing the particular stratigraphic and spatial distribution of these facies associations on both conjugate margins of the South Atlantic, adapted from Saller *et al.* (2016).

The second reservoir type, referred to as the clotted peloidal silica system (CPS: Fig. 4a) (Hunt *et al.* 2019), is typically characterized by seismic wedges and mounded geometries deposited on the flanks of structural and volcanic highs in outer basin structural highs (Fig. 4b) (Saller *et al.* 2016; Hunt *et al.* 2019). It comprises cycles of extensively silicified microbialites, depositional breccias and dolomites. Older parts of the CPS system are known to contain thin coquina intervals, whereas above the basinward extension of the pre-Alagoas unconformity (Fig. 4) the youngest part of this system can also contain thin intervals with spherulite–fibrous fan components (Saller *et al.* 2016; Hunt *et al.* 2019). These CPS reservoirs contain abundant precompaction low-temperature silica cements (Fig. 4aiii–iv) (Saller *et al.* 2016; Lapponi *et al.* 2019) and later hydrothermal silica (Saller *et al.* 2016; Vieira de Luca *et al.* 2017; Lapponi *et al.* 2019). Thus, the CPS system appears to be the distal equivalents of both the CPS depositional system and the spherulite fibrous fan (SFF) depositional system described below, and leads to some debate concerning its affinity to both the BIO and SFF reservoir systems (Fig. 4a, b).

Above a prominent unconformity, known as the Pre-Alagoas unconformity on the Brazilian margin (Moreira *et al.* 2007; Chaboureau *et al.* 2013) (Fig. 4a), the youngest SFF pre-salt reservoirs are characterized by crystalline 'shrubs' and spherulites, associated with magnesian clays and dolomite, corresponding to the Barra Velha Formation in the Santos Basin. The biogenic (microbial) v. abiotic origin of these has been hotly debated (see Muniz and Bosence 2015; Wright and Barnett 2015) but on the Brazilian margin the consensus is that they are largely of abiotic origin and were precipitated by chemical-driven processes within hypersaline–alkaline lakes (Wright and Barnett 2015, 2017; Pietzsch *et al.* 2018, 2020; Wright 2021). However, the synoptic relief of the carbonate accumulations and therefore the water depth at the time of formation has proved a source of continued discussion. A key issue is whether seismically imaged geometries interpreted to represent prograding depositional slopes (i.e. clinoforms: see Buckley *et al.* 2015; **Minzoni *et al.* 2021**) or microbial carbonate build-ups (i.e. Barnett *et al.* 2018; Correa *et al.* 2019; Menezes de Jesus *et al.* 2019), are primary pre-salt depositional geometries or are alternatively seismic imaging artefacts, a result of post-depositional structural deformation or igneous extrusive or intrusive bodies (Wright and Barnett 2017, 2019; Wright and Rodriguez 2018).

Aptian pre-salt deposits on the African margin (Kwanza Basin) are broadly correlative to the Barra Velha Formation but contain facies identified as microbial in origin (Saller *et al.* 2016; Sabato Ceraldi and Green 2017), as well as shrubs and spherulites similar to those of the Barra Velha. Limited seismic data have been published but steep-sided platforms and isolated to amalgamated mounds have been interpreted on the crests of basement fault blocks (Saller *et al.* 2016). Whilst there are numerous modern and ancient alkaline–saline lake microbialites that could serve as partial (small-scale) analogues to these, direct outcrop analogues for the abiotic spherulite and shrub facies are very rare.(cf. Mercedes-Martín *et al.* 2017).

Current debate concerning the interpretation of pre-salt seismic geometries is focused on five topics: (1) Are clinoform geometries real or artefacts derived from a complex salt overburden, syndepositional tectonism or volcanism? (2) Was significant synoptic depositional relief associated with deposition of the shrub–spherulite systems? (3) How should present-day geometries be restored to account for syn- and post-depositional deformation? (4) Is it necessary to account for the scale difference between seismic geometries and those of modern/ancient lacustrine analogues, and how might this be approached? (5) How to differentiate between carbonates and precursor rift volcanics given the overlap in their acoustic properties and some seismic geometries/facies?

At one end of the spectrum of interpretations, some workers consider the post-Alagoas hypersaline–alkaline lake system to be entirely shallow, and that the observed seismic geometries are acquisition artefacts, and/or are otherwise misleading and so have been misinterpreted (Wright and Barnett 2017; Wright and Rodriguez 2018). In contrast, others conclude that the geometries are largely primary, closely mirror those of tropical marine counterparts and that the individual fields represent a complex archipelago of isolated lacustrine carbonate platforms surrounded by deeper waters (e.g. Simo *et al.* 2019; **Minzoni *et al.* 2021**). These different positions also involve additional arguments related to geochemical data and high-frequency correlations in the uppermost part of the pre-salt stratigraphy (Pietzsch *et al.* 2018), so there remains much to finally resolve.

Minzoni *et al.* (2021) utilize a tapestry of high-quality 3D seismic data tied to wells from the northern Santos Basin to reveal a picture of isolated lacustrine carbonate platforms that nucleated on tectonic highs. In both the fresh saline BIO and overlying hypersaline–alkaline SFF lacustrine systems, they interpret clinoformal geometries to indicate water depths of up to several hundred metres. They recognize regionally consistent asymmetry in platform geometry and clinoform progradation that is interpreted to have been controlled by winds that varied on a seasonal basis. These same preferred clinoform orientations are recognized by **Barnett *et al.* (2020)** in the Campos Basin (Olivito and Souza 2020). **Minzoni *et al.* (2021)** also infer regionally consistent accommodation patterns and platform downstepping reflecting long-term changes in lake level. These conclusions follow from an underlying assumption that the carbonate depositional system behaves in a way similar to modern tropical-marine carbonate platforms, with water-depth-dependent production profiles, and facies controlled by water depth, accommodation and wave energy. Such assumptions are common when interpreting apparent synoptic relief developed by lacustrine carbonate systems, and so it is certainly useful to consider if they could apply in this case and, if they do, what interpretations and predictions ensue.

To date, most studies of the bioclastic pre-salt reservoirs have been focused on the African Congo Basin and the Campos Basin of Brazil (e.g. Harris 2000; Olivito and Souza 2020). **Barnett *et al.* (2020)** use well data from the Mero Field in the northern Santos Basin to constrain seismic-scale clinoformal and mounded geometries. They demonstrate how borehole-image-derived dips, corrected to account for later structural tilt, show repeated patterns of low–high dip values that correspond to seismically imaged clinoforms. The preferred orientation of the clinoforms is interpreted to indicate wind-driven submarine currents, much as suggested by **Minzoni *et al.* (2021)** but, in this case, reworking shells from lower-energy settings into spits and bars nucleated on basement ridges. Clearly, some considerable relief was developed during deposition of the biogenic system (**Barnett *et al.* 2020**) and could presumably have been inherited by the succeeding hypersaline lacustrine system.

Reservoir property prediction during exploration is closely associated with seismic-scale geometries and interpreted seismic facies, and it should be noted that understanding of seismic facies in non-marine carbonate depositional systems is still in its infancy, and so caution is required in direct comparison with and the use of the same terminology as marine examples. A key consideration, alluded to by **Barnett *et al.* (2020)**, is the impact of both syn- and post-depositional tectonic activity. This can result in misleading structures and seismic geometries: for example, Brown (2011, p. 121):

> In general, stratigraphic features, after being deposited on a flat-lying surface, will be bent and broken by later tectonic movements. Stratigraphy and structure then become confused and the interpretive task comes in separating them. The structure must be interpreted before stratigraphy can be appreciated.

It is important that future studies utilize complete integration of interpretations of the tectonic evolution of the fields and basins to reach agreement on exactly which aspects of seismic imaged geometries are pre- and post-depositional.

As a final comment, it is important to note that considerable efforts are underway to apply quantitative seismic-inversion and rock-physics methodologies for the purpose of 3D inversion and reservoir model building. Although this important aspect of seismic reservoir characterization in the pre-salt is not covered in this volume, it is beginning to appear in the literature (e.g. Ferreira *et al.* 2019, 2021; Penna *et al.* 2019; Dias *et al.* 2021).

Novel developments in seismic modelling of carbonates

Although seismic data are without doubt extremely useful to image, understand and explore subsurface strata, we also know that interpretation of seismic images is often complicated by significant problems such as poor image quality, and resulting uncertainty about accuracy and uniqueness of interpretation of imaged geological features. Faced with this uncertainty, inverse- and forward-modelling methods are key tools to help make the critical link between 'real' outcrop and interpreted subsurface carbonate geology (e.g. Lanteaume *et al.* 2018). Four papers in this volume use various aspects of the inverse and/or forward modelling to explore how carbonate depositional and diagenetic processes are recorded in carbonate strata and imaged by seismic data.

Inverse methods use mathematical and statistical techniques to recover information from observed seismic data on subsurface physical properties (Barclay *et al.* 2008; Bosch *et al.* 2010). The simplest example takes the reflectivity of rock interfaces, as measured more-or-less directly in seismic data, and converts that to impendence, or other rock properties such as porosity. Inverse modelling can also be used to explore the seismic expression of major diagenetic features such as palaeokarst (see the introduction to **Fournillon *et al.* 2021** below). Details of all the numerous and complex pre- and post-stack inversion algorithms are beyond the scope of this paper but a recent review can be found in Schuster (2017). A key point is that the complex acoustic properties of carbonates mean that precise inversion workflows tend to be case-specific depending, for example, on the rock fabric, fluid type, fracturing or karstification, and on the desired outcome, so analysis via the inverse method is useful but rarely straight forward.

Forward modelling, in contrast to inverse methods, does not start with the original data but, instead, calculates forward in time from some starting condition to determine what would be observed if a given set of processes operated. Processes can take many forms: for example, stratigraphic (Burgess 2012) or seismic (Janson *et al.* 2007; Janson and Fomel 2011). A forward model composed of a reasonable representation of well-understood physical processes is already somewhat calibrated by the information encoded in that process representation, so it should output generally realistic results (Burgess 2012). Careful comparison between the forward-model output and seismic data, perhaps using the data to refine the forward-model parameters to improve the match between models and observations from a specific outcrop or subsurface example, can then provide insight into what is the most realistic interpretation of the seismic image.

If two forward models are combined, one to calculate stratigraphic products of depositional processes and the other to simulate the seismic imaging of those strata (e.g. Lecomte *et al.* 2015; Masiero *et al.* 2020), a synthetic seismic image of a stratigraphic forward model is produced (e.g. Antonatos 2018; **Masiero *et al.* 2021**). Comparing this synthetic seismic image with a seismic image of the real subsurface is a potentially powerful means to understand the formation and significance of sequence-stratigraphic features imaged in the seismic data, such as onlap or truncation. This is because the causal mechanism of the features is fully understood from examination of the stratigraphic forward model without having to make the usual unsubstantiated seismic and sequence stratigraphic assumptions (see Thorne 1992 for an insightful discussion).

Mascolo and Lecomte (2021) employ detailed digital outcrop data to construct synthetic seismic models of the Cretaceous Apulian carbonate platform–slope–basin transition exposed across the Maiella Mountain in central Italy. The aim of the seismic modelling is to use the outcrop as an analogue for subsurface platform margin and slope strata elsewhere: for example, in the Adriatic Sea. Synthetic seismic data are generated in both post-stack-time- and pre-stack-depth-migrated domains to image the spatial distribution and depositional architecture of the slope-failure escarpment and base-of-slope carbonate strata mapped in the outcrops. This approach is novel and pragmatic because the use of seismically imaged outcrops fills the scale gap imposed by seismic resolution limits with critical predictive detail that could usefully reduce some key subsurface uncertainties.

With a similar aim, **Masiero *et al.* (2021)** integrate two forward models to explore how carbonate platforms develop in and respond to synrift tectonic settings. One is a novel 3D stratigraphic forward model that predicts platform architectures and gross facies distributions in response to variables such as fault geometry, displacement rate, tectonic subsidence, climate and eustasy, and the other is a seismic forward model to produce the corresponding acoustic response on 2D sections. The work adds supporting evidence to existing models of synrift carbonate-platform evolution by reproducing the fundamental platform morphologies and facies distribution characteristics described in such conceptual models. However, some results diverge from the standard conceptual model predictions: for example, for the same slip rates, under high-transport regimes the platform is likely to prograde downdip, while in low-transport systems the platform margin quickly backsteps towards the footwall crest. The modelling also suggests that backstepping platform margins may be difficult to identify on seismic images due to bypass slopes with fringing aprons where grainy sediments are mixed with fine-grained facies, generating continuous high-amplitude seismic reflections from the platform interior onto the slope.

A somewhat different approach is adopted to explore a specific example of platform drowning by **Gold *et al.* (2020)**. They derive a well-to-seismic tie across a 600 m-thick 4 myr duration drowning interval at the top of the Yawee Limestone carbonate platform on the southern margin of West Papua. The well tie is then used to refine the seismic depth–velocity model and reprocess the seismic data. Improved seismic imagery is analysed with a seismic inversion and stratigraphic forward modelling method to better understand and predict carbonate and shale facies distribution, porosity, and pore-fluid properties through the heterolithic drowning succession strata. Seismic inversion is discussed in more detail below.

Seismic characterization of fluid flow and diagenesis in carbonates

Seismic inversion, the process of extracting reservoir and fluid characteristics from seismic data, involves making geologically informed assumptions about the physical (elastic) behaviour of the rock matrix (see Avseth *et al.* 2014). Carbonate rocks have faster acoustic velocities, on average, than siliciclastic rocks, coupled with a very high potential for diagenetic modification. The acoustic properties of carbonate rocks have previously been shown to be influenced by mineralogy (e.g. calcite v. dolomite), total porosity, pore shape, amount of microporosity and, to a lesser extent, fluid content (Eberli *et al.* 2003; Xu and Payne 2009; Weger *et al.* 2009). This means that relationships between V_P, V_S, porosity and permeability, and their variations with burial depth, are much less tightly constrained than in siliciclastic sandstones. Empirical data show that some limestones approximate to a common V_P–porosity transform (‘Wylie time-average relationship’), so low-velocity anomalies within strata independently determined to be carbonates can potentially indicate reservoir quality, and acoustic impedance is the attribute commonly used to target reservoir potential. However, early diagenesis can have a major impact on pore stiffness and P-wave attenuation, especially early cementation in grainy limestones, generation of microporosity in muddy limestones and dolomitization (e.g. Brigaud *et al.* 2010; Vanden Berg *et al.* 2018; Salih *et al.* 2021). Significantly, oil emplacement may have a lesser impact on pore stiffness and, hence, V_P than on total porosity because cementation may still take place in the water-wet microporous grains, increasing their rigidity. Whilst numerous experimental and theoretical studies have attempted to characterize carbonate rock physics in texturally simple cases, dual or even treble porosity systems occur in many reservoirs (e.g. microporosity, interparticle and moldic porosity, fractures and connected vugs). Such reservoirs may be unique cases requiring direct calibration from well data, or at least careful geological assumptions about depositional and diagenetic processes and their resultant geometrically categorized pore fabrics (e.g. Warrlich *et al.* 2010; Fournier *et al.* 2014, 2018).

Laboratory measurements have shown that the fluid effect on acoustic properties in carbonate rocks is small in magnitude, and more complex in nature (i.e. less predictable) than in their siliciclastic counterparts. Because of their anisotropic heterogeneous pore networks and complex diagenetic histories, carbonate rocks may not follow simple rock mechanical rules like the Gassmann equation (Baechle *et al.* 2005, 2009; Vanorio *et al.* 2008; Verwer *et al.* 2008), although this is still used as a reference: for example, where homogeneous matrix porosity is augmented by variable amounts of fracture porosity (e.g. Hammond and Payne 2013). As a result of these complexities, interpretation of the seismic signal in carbonates can be challenging as the interpreter has to decide whether seismic reflections follow geological time lines, as assumed by the seismic stratigraphy principles (Eberli *et al.* 2002), or whether reflection geometries are influenced by diagenetic modifications that can cut across time lines (e.g. Fournier and Borgomano 2007; Warrlich *et al.* 2010; Teillet *et al.* 2020).

Liquid substitution in the pore space (brine to oil, for instance) results in very small changes in impedance, making liquid direct hydrocarbon indicators (DHIs) in carbonate system seismic data very difficult to detect (Rafavich *et al.* 1984; Adam *et al.* 2006). As a consequence, the most common DHIs in carbonates are created by gas–water contacts within high-porosity reservoirs, although these are probably reliable only with a thick reservoir interval and/or lower impedance of the gas leg than overlying shale, or with high-quality S-wave data and V_P/V_S calibration from nearby or representative wells (Sams *et al.* 2017). Gas chimneys are also a useful indirect DHI where carbonate reservoirs are breached, causing vertical zones of frequency and amplitude attenuation (e.g. Vahrenkamp *et al.* 2004; Roberts and Peace 2007). Although velocity pushdowns might be anticipated below gas-filled carbonate reservoirs, in practice these are likely to be masked by velocity pull-ups from the acoustically fast carbonate lithology. The relatively few successful 4D seismic studies in carbonates show examples of gas–water contact displacement in carbonate reservoirs (Carpenter 2019; Warrlich *et al.* 2019; Teillet *et al.* 2020) (Fig. 5). This can be powerful when combined with multi-attribute workflows that reveal fault

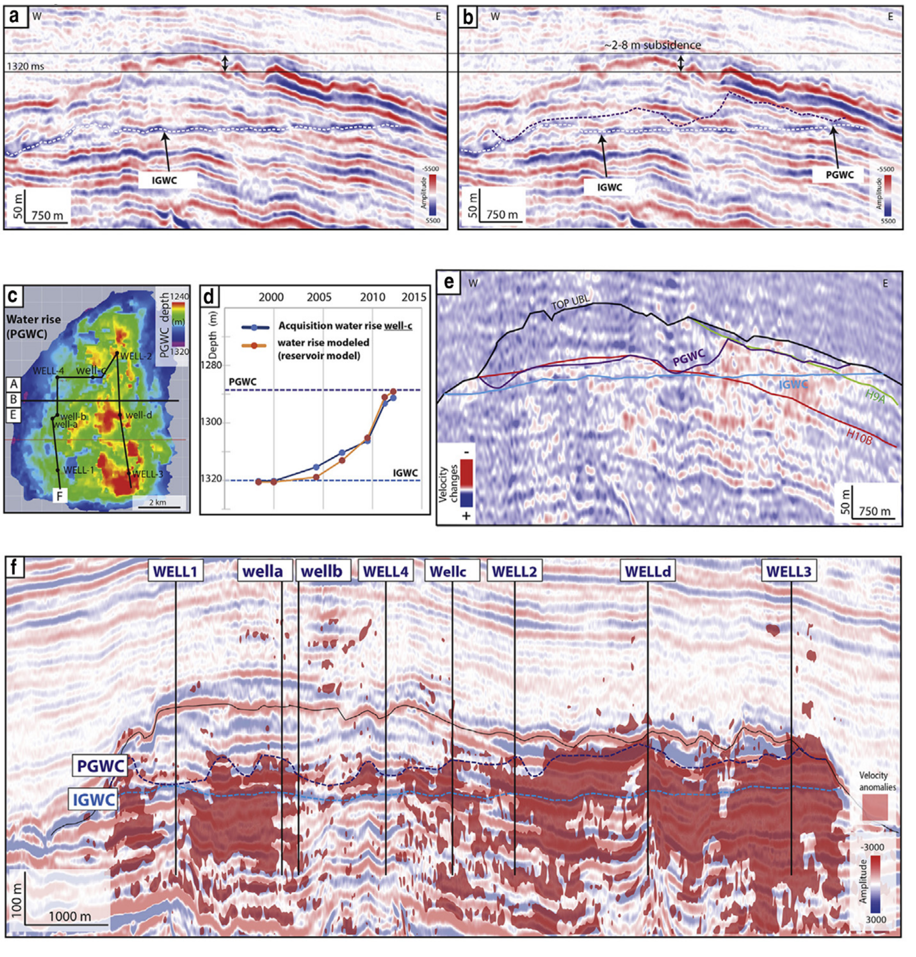

Fig. 5. Example of time-lapse (4D) seismic analysis of a carbonate gas reservoir from offshore Myanmar. The high stiffness of the carbonate rock matrix and the stratigraphic heterogeneity of porosity and impedance characteristics mean that flat spot DHIs can rarely be discriminated in carbonates. However, the presence of high gas saturations can be manifest in lower acoustic velocities compared to brine-filled equivalents. In this case the top of a velocity anomaly between the original and monitor seismic is used to map the present-day gas–water contact (PGWC) and thus its change over a 19-year production history. Note the reflector at the initial gas–water contact (IGWC) cross-cutting the stratigraphy and interpreted as a diagenetic boundary marking different porosity evolution in the gas and water legs. Depositional and diagenetic heterogeneities are responsible for the uneven rise of the fluid contact. Modified from Teillet *et al.* (2020). (**a**) and (**b**) show identical profiles from the 1993 and 2021 3D surveys. (**c**) and (**d**) show the rise in the gas-water contact by 2012 as a map and through time at well c. E shows the seismic p-wave velocity changes between 1993 and 2012 on the same profile as in (a) and (b). UBL, Upper Burman Limestone Formation; H9A and H10B are seismic markers. (**f**) composite seismic profile showing the change in the gas-water contact and the distribution of the velocity anomalies resulting from production between 1993 and 2021. Location of all profiles is shown in (c).

sets that may be influencing production (Astratti *et al.* 2015).

Amplitude v. offset (AVO) and extended elastic impedance (EEI) trends are commonly and powerfully employed to predict both lithological (e.g. shale to sand) and fluid (gas–oil–brine) contacts in siliciclastic systems (see the review by Fawad *et al.* 2020) but AVO has been employed less and EEI hardly used in carbonates to date. This is because the matrix (rock) and pore geometry heterogeneity are poorly constrained pre-drill, and can influence the acoustic response with offset angle as much or more than the fluid content. Exceptions are mostly limited to texturally uniform low impedance–high porosity reservoirs such as some dolostones or chalks, and to some mixed mineralogy and palaeokarst reservoirs (Li *et al.* 2003, 2016; Jaspen *et al.* 2005; Vejbæk *et al.* 2005; Hammond and Payne 2013; Pernin *et al.* 2018). Even in these cases the analysis requires significant integration of well-log and core data to build a robust rock-physics model (Li and Downton 2000), and is therefore used in field development rather than exploration. It is also important to note that whilst coarse porous dolomites may behave in a similar fashion to sandstones with regard to AVO, the interpretative 'AVO classes' cannot be transposed (Li *et al.* 2003). Another example where AVO may have potential is in fractured carbonate reservoirs, because fracture presence can significantly reduce the stiffness of the rock matrix, and their orientation has a significant impact on the attenuation of S-waves in particular. High-quality log data are again vital for calibration.

Carbonate platform and reservoir strata are very susceptible to dissolution that can create seismic-scale features such as palaeokarst. The seismic expressions of epikarst have been studied for a long time (Brown 1985). Recent advances stem from reservoirs associated with major unconformities such as the Middle Ordovician in China and Texas, or the Devonian in Canada where 3D seismic data and well information are common, or because of the drilling hazard cause by karst caverns. Studies have either employed 3D seismic geomorphological techniques, including surface attributes, volume attribute slicing and frequency blends (e.g. Sullivan *et al.* 2007; Ting *et al.* 2010; Zeng *et al.* 2011; Fernandez and Marfurt 2013; Zampetti *et al.* 2014; Tian *et al.* 2019; Cross *et al.* 2021; **Embry *et al.* 2021**) (Fig. 6), or 3D seismic modelling to show the various amplitude responses in both vertical section and horizontal slices of palaeokarst (e.g. Janson and Fomel 2011; Decker *et al.* 2015; Jensen *et al.* 2021). Advances in seismic acquisition with high fold and wide azimuth acquisition, as well as advanced and full azimuthal processing, have demonstrated increased resolution in seismic imaging of palaeokarst (Feng *et al.* 2012; Wang *et al.* 2012).

A greater challenge is in identification of hypogene karst that is typically associated more with fault and fracture networks than with unconformities, and is therefore more extensive in the vertical plane than in areal extent, more difficult to image and more susceptible to velocity artefacts associated with the structuration. Sometimes it is only identifiable from collapse features in the non-carbonate overburden (Sun *et al.* 2013). Recent studies have shown how epikarst systems may act as subsequent conduits for hypogenic karst-forming fluids (Howarth and Alves 2016; Cross *et al.* 2021). Pipe-like conduits for focused fluid flow have been less illustrated in carbonate strata than in siliciclastics

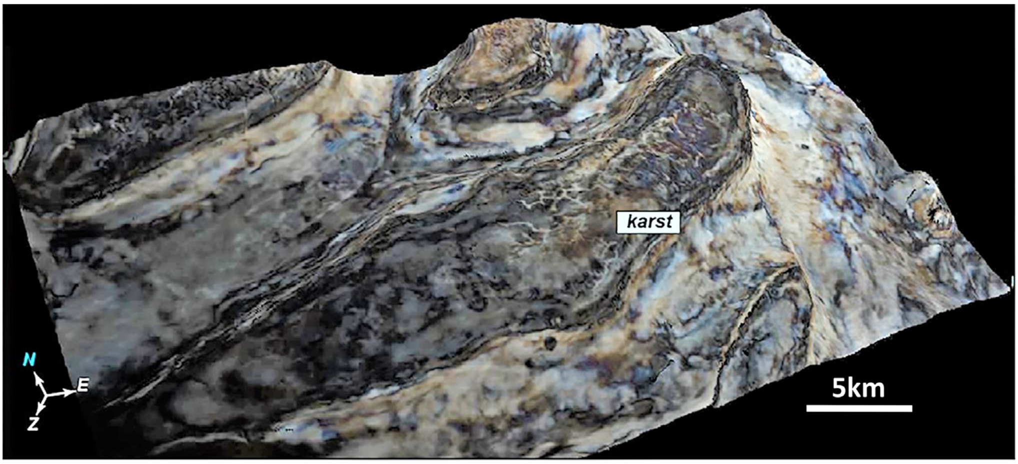

Fig. 6. Spectral decomposition extraction draped on a 3D surface showing dendritic karst network developed on top of a Miocene carbonate platform in Luconia, South China Sea (modified from Makhankova *et al.* 2020, fig. 8f).

but can be spectacularly imaged on 3D data (Fig. 3). Interest in hydrothermal dolomite plays led to several studies using 3D seismic attributes and/or post-stack noise-removal processing to image the porosity or attempt (with variable success) to map dolomite (e.g. Hart *et al.* 2009; Ogiesoba 2010; Zhu *et al.* 2017). A drawback is that most hydrothermal dolomite plays are onshore, where there is typically abundant well data, including core samples, but limited high-quality 3D seismic, whereas offshore is characterized by much less borehole data for calibration. Solum *et al.* (2017) used a novel scenario modelling and synthetic seismic approach to test the efficacy of multiple 3D volume attributes for distinguishing non-stratabound dolomite-associated porosity, finding the best results for attributes sensitive to lateral changes in rock properties (semblance, cosine of phase), followed by amplitude-related attributes, with frequency attributes giving the least discrimination.

Large-scale palaeokarst systems are now relatively easy to identify using appropriately high-quality 3D seismic datasets, and recent advances highlight the ability of machine learning to automatically extract karst geobodies from 3D seismic data (Wu *et al.* 2020). Seismically resolving smaller or more diffuse karst systems and subaerial exposure events can be challenging, and may always require integration of well-log and core data to reduce uncertainties to a realistic level (Teillet *et al.* 2020). Nevertheless, the combination of amplitude and frequency data provided by spectral decomposition attributes provides a powerful means of imaging ancient karst landscapes on carbonate platform palaeosurfaces (e.g. Qi *et al.* 2014; Yuslandi *et al.* 2019; **Embry *et al.* 2021**).

Fournillon *et al.* (2021) combine stratigraphic and forward seismic modelling to explore the seismic expression of various exposure events of short to long (<10 to >100 kyr) duration on an isolated carbonate platform comparable to Miocene reservoirs in SE Asia. The impact of some simple but essentially realistic porosity and P-wave velocity model representations of karstification resulting from short (10 kyr), medium (10–100 kyr) and long-term (>100 kyr) subaerial exposure is determined by comparison with a non-karst reference 3D geological model. The authors model the location and magnitude of palaeokarst development related to a freshwater lens and coastal (mixing zone) palaeokarst, and compute the resulting seismic images using a 1D convolution approach. The results demonstrate that exposure-related karst features can be stratiform or non-stratiform but the two are often difficult to distinguish in the modelled seismic images. Thus, dendritic caves, platform flank-margin caves and platform interior cave networks are shown to be detectable in amplitude sections, non-stratiform or large-scale but lower-porosity karst features were difficult to discriminate without additional attributes. This implies that seismic image data alone may not significantly reduce key uncertainties in cases where karstification affects reservoir properties (e.g. cave-collapse breccias), although significantly useful additional information may be present in coherency data. Moreover, the inversion modelling is shown to be an important step in producing geologically realistic seismic palaeokarst images that could be combined with other seismic-stratigraphic forward-modelling approaches such as those of **Masiero *et al.* (2021)**.

Seismic evidence of fluid flow in carbonates is not well documented and is typically manifested in shallow, high-impedance amplitude anomalies that represent cementation of weakly lithified Cenozoic strata, and which are spatially and geometrically associated with imaged faults (e.g. Abdulkareem *et al.* 2019). However, **Smit *et al.* (2021)** address both fluid flow and diagenesis in more deeply buried pelagic chalk, where such features can be beautifully imaged owing to the relatively uniform carbonate matrix. Integrating 3D seismic data, well data (logs and cuttings) and basin modelling, they interpret Cretaceous-age mega-pockmarks and seep-related diagenetic cementation at specific levels within the Santonian–Campanian Chalk Group of the Danish Central Graben and link them to thermogenic gas generation from deeply buried Carboniferous coals. The mega-pockmarks occur in quasi-linear trains and were previously attributed to depositional processes (contourite moats and/or channels eroded by turbidity currents) but 3D analysis and semi-automated horizon-by-horizon interpretation with spectral decomposition reveal them to be discrete shallow bowl-like depressions associated with underlying vertical discontinuity zones and high-amplitude anomalies. The pockmarks are interpreted to have formed through transient fluid venting and sediment resuspension, whilst the high-impedance anomalies are shown to arise from cementation by methane-derived carbonate. Fluid ‘pipes’ and palaeo-pockmarks related to hydrocarbon leakage are widely documented from siliciclastic passive margins but hitherto rarely described from carbonates.

Future trends and opportunities

Seismic technology continues to advance at a rapid pace, with improvements in acquisition, processing, inversion and visualization offering the potential to improve the quality and scope of 3D seismic interpretation in carbonates (e.g. Hager 2019). As costs come down, there is more opportunity for these to be used at exploration stage as well as for detailed reservoir characterization. Acquisition improvements include: (i) long offsets, multiple sources and novel source–receiver geometries to increase data density; (ii) wide- and multi-azimuth shooting to improve illumination, reduce noise and better image fractures; and (iii) improved broadband technology giving a more uniform frequency response, improved depth penetration, and higher resolutions to detect facies boundaries, fracture networks and diagenetic features such as palaeokarst with greater precision. The constant challenge is to reduce artefacts whilst maintaining the integrity and enhancing the quality of primary target data, especially where near-surface complexities, excess noise 'contamination' or acquisition constraints (e.g. onshore or transition zone) are involved. A new development to improve imaging in existing carbonate fields is hybrid streamer and ocean-bottom node acquisition, which permits an approach towards full azimuth and offset distribution. Advances in processing include diffraction modelling and imaging to separate diffraction energy on pre-migrated data and so to better image karst voids and small-scale heterogeneities (Decker *et al.* 2015), plus important enhancements in velocity model building such as transverse tilted isotropy (TTI), which can better image fractures and igneous bodies than conventional isotropic tomography models (e.g. Penna *et al.* 2019).

Rapid increases in computer power provide opportunities to build ever more detailed velocity models. Seismic inversion is an area of rapid technological and computational development, especially regarding post-stack geostatistical and rock-physics-based inversion to produce seismic facies for improved geobody interpretation and reservoir model population (e.g. Al-Ali *et al.* 2020; Ghon *et al.* 2021; Teillet *et al.* 2021). Full waveform inversion (FWI), using borehole vertical seismic profile (VSP) data to directly estimate elastic parameters with depth, has been successfully applied to several carbonate reservoirs (e.g. Takougang *et al.* 2020) and may become more commonplace in the future as an exploration tool conditioned with data from distal wells (Kjøsnes *et al.* 2018). New developments look to improve FWI by using information extracted from surface waves and guided waves to update the velocity model in the very shallow zone where complexities are present. Multi-azimuth data will permit fracture-related anisotropy to be more accurately built into velocity models so that they are best tailored for the carbonate reservoir in question. Improvements in depth migration (e.g. least-squares methods and common offset vectors to preserve azimuthal data) will also improve the resolution and subsequent interpretation of fractured carbonates.

With improved frequency content from advances in acquisition, the spatial and rock-physical resolution of geomorphological features that can be imaged through spectral decomposition is continuing to increase to the extent that carbonate depositional palaeoenvironments can be viewed in remarkable detail (Fig. 7). Combined with technologies to auto-pick and correlate individual stacked reflectors through a data cube there, it may soon be possible to view and map the palaeogeographical development of carbonate platforms through time – effectively creating 3D movies of how platforms grow and evolve in response to autogenic and allogenic controls. Additional interpretative power is being generated by improved attribute quality and multi-attribute co-rendering, with particular refinements in coherency attributes enabling more detailed and quantitative assessments of fracturing and karstic discontinuities. A concurrent trend is the development of carbonate rock-physics models based on digital imaging of rock samples, as well as theoretical approaches that more precisely relate porosity, pore shape and elastic properties. The fact that the latter are strongly influenced by diagenesis may become an opportunity to use high-quality seismic data to map out diagenetic geobodies, with increased computational power able to run multiple scenarios to explore how diagenetic heterogeneity is most likely to be expressed on seismic images.

More generally, machine learning and related data-science methods may provide an opportunity for substantial automation in basic seismic interpretation, such as horizon and fault picking and attribute selection, freeing time and expertise for geological interpretation, well planning and reservoir modelling. However, many machine-learning algorithms derive their power, beyond the basic algorithms, many of which have existed for decades, from large datasets that can train the learning method. If a suitably large dataset is available, once trained they can do specific things very well but it remains to be seen to what extent 3D carbonate seismic datasets are big enough with data of the right type. Also, it should be noted that these algorithms, while effective, are still very specialized and require dedicated training with specific data (e.g. Wu *et al.* 2020). Nothing yet exists like the biological general learning 'master algorithm' (Domingos 2015) that humans appear to employ, so the use of the term 'machine learning' with the implied links to how people learn is still, perhaps, quite misleading. Given these caveats, and despite what seems like an opportunistic tendency to jump on the machine-learning and data-science bandwagon, it seems likely that a hybrid approach employing both machine and human learning, rare though the latter sometimes seems, will be likely to remain the best approach for some time to come. Put another way, the need for skilled and experienced carbonate geoscientists to 'keep the algorithms honest' will remain (and potentially increase) in parallel with automated approaches to seismic facies classifications and interpretations.

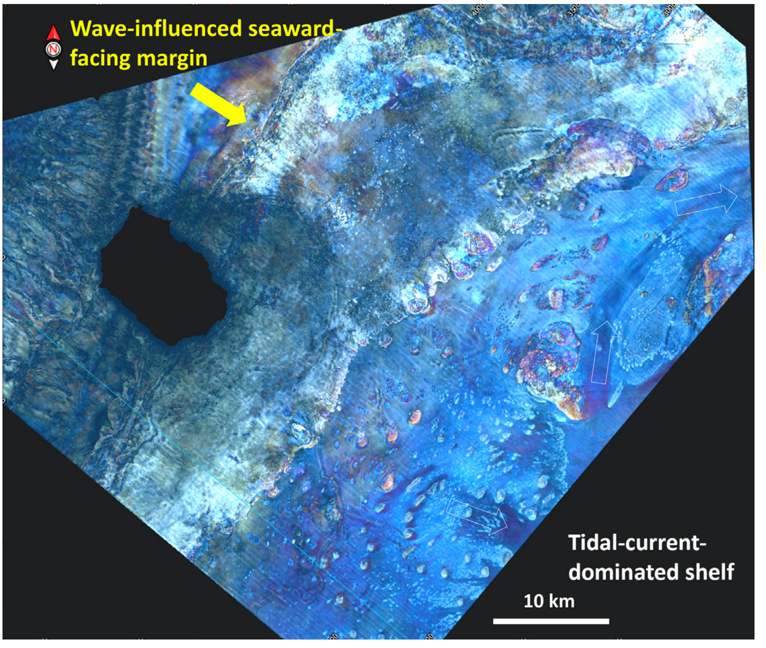

Fig. 7. Frequency decomposition surface extraction of a Miocene carbonate platform and shelf in the Browse Basin of Australia showing the complex architecture and morphology of a shelf-margin platform exposed to ocean swell, and a shelf interior shaped by tidal currents (Janson pers. comm. 2021). Data courtesy of Geoscience Australia.

Finally, as the energy transition progresses, and extraction and burning of hydrocarbons is replaced by energy generation from more sustainable sources, the very large volume of seismic data acquired to image carbonate reservoirs and potential reservoirs is going to need to be preserved as an important scientific resource that will continue to advance knowledge of carbonate systems in deep time. Given the value and the volume of data, and the storage costs likely to be involved, this is an important area that requires attention. All the data, and new data of a similar type, could also be potentially redeployed onto new projects related to exploration for sustainable energy resources: for example, geothermal carbonate reservoirs (e.g. Von Hartman *et al.* 2012; Montanari *et al.* 2017; Reijmer *et al.* 2017) or strategically important mineral resources. New project applications are also likely to include sequestration of carbon dioxide into depleted hydrocarbon reservoirs (e.g. Lueck *et al.* 2016; Raza *et al.* 2017). All of which would also make use of the significant geological and geophysical expertise presented and discussed in the 2018 international meeting and in this subsequent volume, allowing seismic characterization of carbonate platforms and reservoirs to continue to make an important contribution to the growth of pure and applied scientific knowledge.

Conclusions

Major advances in seismic imaging of carbonate strata over the past 10–15 years have revolutionized geological understanding of carbonate accumulation, with implications from hydrocarbon exploration to geomorphology and palaeoclimate change. This review and contextualization of the papers in this volume summarizes these developments, including the creative ways seismic data can be used in exploration for carbonate plays, and in subsequent field development, including for the unique giant ‘pre-salt’ non-marine carbonate fields of the central South Atlantic that have been the focus of much debate in recent years. New developments in seismic modelling of carbonates and integration with forward models of carbonate deposition and accumulation are discussed, and seismic evidence for fluid flow and diagenetic modification of carbonates, especially karstification, are considered. Seismic attributes and frequency blends draped over mapped surfaces have proved to be powerful tools for revealing facies belts such as platform margin barrier reefs, patch reefs and lagoons, gullied platform slopes, slumps, and carbonate contourite drifts, as well as karst landscapes of sinkholes and dendritic cave networks. Carbonate seismic data are most valuable where interpretations are integrated with results from other disciplines, such as structural restoration, basin models, borehole wireline logs including image logs, biostratigraphy and sequence stratigraphy.

Whilst extracting the maximum useful information from the seismic data is essentially geophysics, its interpretation is driven by geological skill and experience, and generates new geological knowledge of carbonate processes and systems. Data quality is fundamentally impacted by the acquisition and processing workflows, which in turn need to be optimized for the anticipated carbonate geology and the associated acoustic properties. It should be evident that close collaboration of carbonate specialists with geophysicists at all stages of a seismic programme affords the best opportunity for mapping the development of platforms, their internal facies belts and diagenetic heterogeneities. Owing to the typical complexity and heterogeneity of their pore networks carbonates can have unique V_P–V_S–porosity–permeability relationships, although a general V_P–porosity trend is obeyed in many cases and acoustic impedance is a good (if not fail-safe) first-order predictor of reservoir presence. Fluids have relatively little impact on impedance except at high porosities and gas saturations, so DHIs are less easily identified in rigid platform carbonates than in poorly lithified sands. A few studies have, with good borehole control, determined AVO relationships in individual carbonate reservoirs but its use as an exploration screening tool is still almost negligible.

A fundamental consideration is that study of present-day or outcrop 'time-snapshots' often do not reveal how carbonate platform development, on millennial timescales and kilometric length scales, was forced by long-term sea level, oceanographic or tectonic factors, yet this forcing can now be determined from modern high-quality seismic images that reveal platform architectures and facies belts both in 3D and through time. This is particularly true for the Lower Cretaceous 'pre-salt' fields offshore Brazil that do not have many direct analogues at outcrop. Interpretation of seismic data from these still provokes lively debate, especially as to whether deposition of these non-marine carbonate systems responded in a similar fashion to the well-known sedimentary dynamics of shallow-marine carbonate platforms. Fundamental considerations, such as whether the deposition took place in shallow or deep alkaline lakes, and the role of syn- to post-depositional tectonics, remain to be resolved. It is likely that consensus will be built as more data from the Santos and Campos basins (and their conjugate margin analogues off west Africa) is released and published, and improved sub-salt processing and velocity modelling help to constrain interpretations. It may well turn out to be the case that the 'pre-salt' lakes and their carbonate platforms were more varied than we think, so multiple models and interpretations are required to understand them.

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